AD-A095 192 ROCKWELL INTERNATIONAL THOUSAND OAKS CA ELECTRONICS--ETC F/G 17/1
ACOUSTIC STONELEY-WAVE SENSOR FOR TOWED ARRAY APPLICATIONS.(U)
DEC 80 E J STAPLES N00014-79-C-0954
UNCLASSIFIED ERC41040.1FR NL

1 OF 1
AD A
095 192

END
DATE
FILMED
3-81
DTIC

ERC41040.1FR

LEVEL

(12)

ERC41040.1FR

Copy No. 21

ACOUSTIC STONELEY-WAVE SENSOR FOR TOWED ARRAY APPLICATIONS

FINAL REPORT FOR THE PERIOD
September 17, 1979 through September 16, 1980

GENERAL ORDER NO. 41040
CONTRACT NO. N00014-79-C-0954

DTIC
ELECTE
FEB 18 1981
C

Prepared for

Office of Naval Research
800 N. Quincy Street
Arlington, VA 22217

Edward J. Staples
Principal Investigator

DECEMBER 1980

Approved for public release; distribution unlimited.

Rockwell International

AD A095192

DDC FILE COPY

81 2 17 079

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER	2. GOVT ACCESSION NO. AD-A095192	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) ACOUSTIC STONELEY-WAVE SENSOR FOR TOWED ARRAY APPLICATIONS		5. TYPE OF REPORT & PERIOD COVERED Final Report. 17 Sep 79-16 Sep 80 9-17-79 thru 9-16-80
		6. PERFORMING ORG. REPORT NUMBER ERC41040.1FR
7. AUTHOR(s) Edward J. Staples		8. CONTRACT OR GRANT NUMBER(s) N00014-79-C-0954
9. PERFORMING ORGANIZATION NAME AND ADDRESS Microelectronics Research & Development Center Rockwell International Corporation Thousand Oaks, California 91360		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Scientific Officer, Director Acoustic Technology Programs, Office of Naval Research Arlington, Virginia 22217		12. REPORT DATE December 1980
		13. NUMBER OF PAGES 41
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) 12 41		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

Approved for public release; distribution unlimited.

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Piezoelectric materials
Acoustic wave propagation
Stoneley wave propagation
Underwater sound sensors

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report describes the results of an investigation of Stoneley interface waves in underwater sound sensors. An analysis of stoneley wave propagation at the interface of anisotropic and piezoelectric crystals is presented and results for single crystal copper, quartz, and lithium niobate are discussed in terms of wave displacements, piezoelectric coupling and wave velocity.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

411391

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE(When Data Entered)

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE(When Data Entered)

TABLE OF CONTENTS

Accession For
NTIS GRA&I
DTIC TAB
Unannounced
Justification
By
Distribution/
Availability Codes
Avail and/or
Dist Special
A

LIST OF FIGURES

LIST OF TABLES

1.0 SUMMARY

The objective of this study was to assess the feasibility of developing a single crystal pressure sensor using Stoneley waves. A theoretical study of Stoneley wave propagation for the case of a single material but different orientations was carried out on cubic materials as well as non-cubic but piezoelectric quartz and lithium niobate, $LiNbO_3$. The results of these studies show that strongly bound Stoneley waves propagate along the major axes of cubic materials. Similar analysis carried out on quartz and $LiNbO_3$ show that only the YZ cut of $LiNbO_3$ supports Stoneley waves. These waves are loosely bound and have an electromechanical coupling coefficient of 1×10^{-4}. Our conclusions are that a Stoneley wave sensor is feasible on YZ $LiNbO_3$ but not on the major cuts of quartz. We recommend continued studies to optimize Stoneley wave search techniques, studies of more materials for Stoneley wave devices, and experimental device fabrication to confirm these results.

2.0 BACKGROUND

High sensitivity, underwater sensors are needed for acoustic surveillance at great depths, typically 1000-3000 ft. Hydrostatic pressures at these depths are extremely large reaching values as high as 1500 psi. Existing ceramic transducers using the piezoelectric effect experience depoling, aging, and other undesirable behavior under large hydrostatic pressures. To avoid depoling and to enhance their sensitivity, such sensors are used with a high dc bias voltage. This leads to complicated and cumbersome electronic arrangements. Many of these ceramic materials are sensitive to water, thus requiring costly protective coatings. All of these problems compound an already severe problem of instability or aging of the ceramic material itself. There is at present a need for underwater sensors which are capable of high sensitivity under large hydrostatic pressure, low in cost, rugged, insoluble in seawater, and require simple electronics.

The objective of this program was to assess the feasibility of developing single crystal pressure sensors for towed array applications under large hydrostatic pressures using a Stoneley wave structure as shown in Fig. 1. Our goal was to conduct a theoretical and if possible experimental study of Stoneley wave propagation and sensors. Hence a major part of this program was to develop a computer program to study the wave propagation of Stoneley waves in anisotropic piezoelectric materials.

The operation of the Stoneley wave sensor shown is similar to a recently developed[1] surface acoustic wave hydrophone sensor. In these

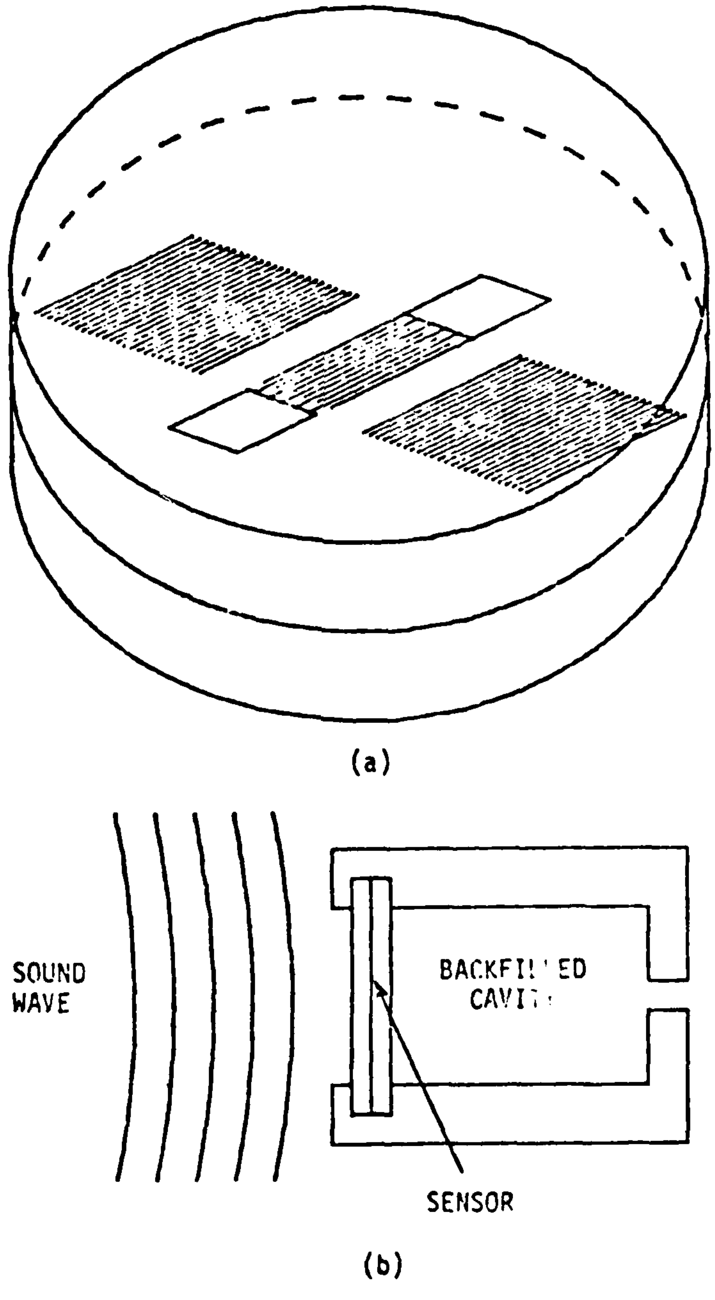


Fig. 1 (a) Stoneley wave underwater sensing element;
(b) Backfilled mount for large hydrostatic pressure surveillance applications.

structures a high Q resonating electrode pattern is used. Flexure and/or compression of the crystal causes a frequency shift from the quiescent resonant frequency. If the crystal is used as the frequency control element of a highly stable oscillator, frequency modulated (FM) sidebands are created when underwater sound impinges on the sensing crystal. Using surface acoustic wave resonators, sensitivities as high as -180 dB re 1 V/μ Pa have been demonstrated.[1]

Surface acoustic wave sensing crystals cannot be used under large hydrostatic pressures because only one side of the crystal can be exposed to the surrounding seawater. However the Stoneley wave structure does not have this limitation. Because the Stoneley waves are bound to the interface between two dissimilar crystals and do not interact with the outward surfaces, the resonant electrode pattern is isolated from these surfaces. This fact would allow hydrostatic pressure to be equalized by applying water to each side of the structure.

To date Stonely wave have not been used in resonant crystal structures. In general two dissimilar materials are required[2] to sustain Stoneley waves at their common boundary. Not all materials, however, form the proper boundary conditions. In fact, only a very few, a point made by a study[3] of 900 materials in which only 30 combinations resulted in Stoneley waves.

However, as pointed out by Lim and Musgrave,[4] a single crystalline material can be used for both top and bottom materials, provided different orientations are used. The boundary in this case if formed due to the

anisotropic nature of the interface. Lim and Musgrave demonstrated this using single crystal copper, a simple non-piezoelectric cubic material. In this report their work has been extended to more complex anisotropic crystals which are also piezoelectric.

3.0 THEORETICAL FORMULATION

3.1 Stoneley Wave Propagation

Consider an interface wave propagating along the X-axis of two anisotropic media as shown in Fig. 2. The X-axis is normal to the interface itself. Any wave propagating in this system must satisfy the wave equation,

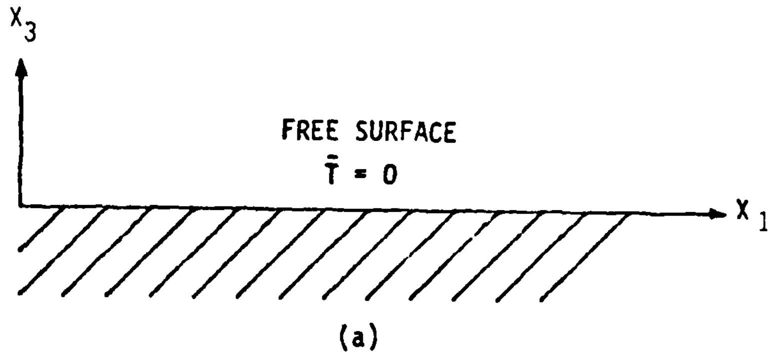
$$\frac{\partial T_{ij}}{\partial X_i} = \rho \frac{\partial^2 U_j}{\partial t^2} \tag{1}$$

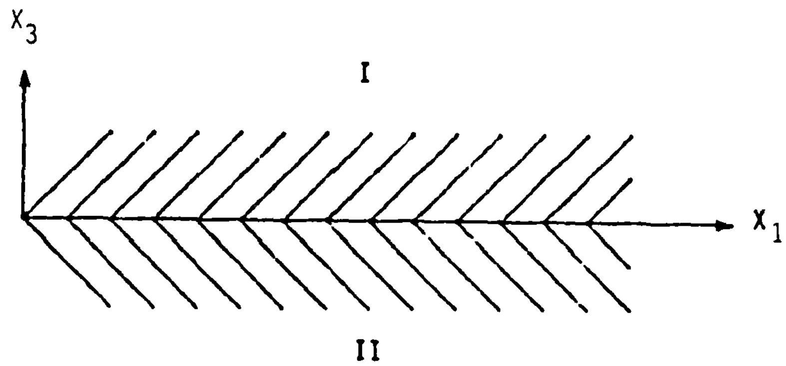
where T_{ij} is the stress tensor, U_j is the mechanical displacement and ρ is the density. The electrical displacement current density, D, for a dielectric material must also satisfy the divergence relationship,

$$\frac{\partial D_i}{\partial X_i} = 0 \tag{2}$$

For piezoelectric materials, the equations of state are as follows:

$$T_{ij} = c^E_{ijkl} S_{kl} - e_{kij} E_k \tag{3}$$





$$T_Z(I)\Big|_{X_3 = 0} = T_Z(II)\Big|_{X_3 = 0}; \; U(I)\Big|_{X_3 = 0} = U(II)\Big|_{X_3 = 0}$$

(b)

Fig. 2 (a) Surface acoustic wave boundary conditions; (b) Stoneley wave boundary conditions.

$$D_i = e_{ikl} S_{kl} + \varepsilon^S_{ik} E_k \tag{4}$$

where the strain tensor, S_{kl}, is related to components of displacement by

$$S_{kl} = \frac{1}{2}\left(\frac{\partial U_k}{\partial X_l} + \frac{\partial U_l}{\partial X_k}\right) \tag{5}$$

and the electric field, E, is expressed as the negative gradient of a scalar potential,

$$E_k = - \frac{\partial \phi}{\partial X_k} \tag{6}$$

The elastic constants of the material are expressed by the tensor, c^E_{ijkl}; the piezoelectric properties by the tensor, e_{ikl}; and the dielectric properties by the tensor, ε_{ik}. In this formulation the piezoelectric elements are evaluated at constant electric field and dielectric properties are evaluated at constant strain.[5]

Substituting Eqs. (3)-(6) into (1) and (2) yields the following equations

$$\frac{1}{2}\, c^{E}_{ijkl}\, \frac{\partial}{\partial X_i}\left(\frac{\partial U_k}{\partial X_l} + \frac{\partial U_l}{\partial X_k}\right) + e_{kij}\, \frac{\partial^2 \phi}{\partial X_i \partial X_k} = \rho\, \frac{\partial^2 U_j}{\partial t^2} \tag{7}$$

$$\frac{1}{2}\, e_{ikl}\, \frac{\partial}{\partial X_i}\left(\frac{\partial U_k}{\partial X_l} + \frac{\partial U_l}{\partial X_k}\right) - \varepsilon^{S}_{ik}\, \frac{\partial^2 \phi}{\partial X_i \partial X_k} = 0 \tag{8}$$

A Stoneley wave propagating along the interface is assumed to have the form,

$$U_j = \alpha_j\, e^{ikbX_3}\, e^{ik(x_1 - vt)} \tag{9}$$

where U_j are particle displacement vectors along X_j-axes; wavenumber $k = 2\,\pi/\lambda$; b is the decay constant with depth; and v is the phase velocity. The scalar electric potential is assumed to follow a similar relationship,

$$\phi = \alpha_4\, e^{ikbX_3}\, e^{ik(x_1 - vt)} \tag{10}$$

Substituting these propagating wave forms into the above equations of motion ((7),(8)) yields the secular matrix equation,

$$\begin{pmatrix} \Gamma_{11}\ ev^2 & \Gamma_{12} & \Gamma_{13} & \Gamma_{14} \\ \Gamma_{12} & \Gamma_{22}-\rho v^2 & \Gamma_{23} & \Gamma_{24} \\ \Gamma_{13} & \Gamma_{23} & \Gamma_{33}-\rho v^2 & \Gamma_{34} \\ \Gamma_{14} & \Gamma_{23} & \Gamma_{34} & \Gamma_{44} \end{pmatrix} \cdot \begin{pmatrix} \alpha_1 \\ \alpha_2 \\ \alpha_3 \\ \alpha_4 \end{pmatrix} = 0 \qquad (11)$$

where

$$\begin{aligned} \Gamma_{11} &= c_{55}b^2 + 2c_{15}b + c_{11} \\ \Gamma_{22} &= c_{44}b^2 + 2c_{46}b + c_{66} \\ \Gamma_{33} &= c_{33}b^2 + 2c_{35}b + c_{55} \\ \Gamma_{12} &= c_{45}b^2 + (c_{14} + c_{56})b + c_{16} \\ \Gamma_{13} &= c_{35}b^2 + (c_{13} + c_{55})b + c_{15} \\ \Gamma_{23} &= c_{34}b^2 + (c_{36} + c_{45})b + c_{56} \\ \Gamma_{14} &= e_{35}b^2 + (e_{15} + e_{31})b + e_{11} \\ \Gamma_{24} &= e_{34}b^2 + (e_{14} + e_{36})b + e_{16} \\ \Gamma_{34} &= e_{33}b^2 + (e_{13} + e_{35})b + e_{15} \end{aligned} \qquad (12)$$

and the electric term is given by

$$\Gamma_{44} = -(\varepsilon_{33}b^2 + 2\varepsilon_{13}b + \varepsilon_{11}) \qquad (13)$$

The secular Eq. (11) is now applied to the top and bottom substrate regions and the matrix of coefficients evaluated. This yields a matrix of coefficients in the unknown decay constant b and the wave velocity v. For a given wave velocity v, the matrix of coefficients is expanded into a polynominal in b which in the completely general case is an 8th order polynominal. The solutions to the polynominal are 8 complex roots or decay constants, b_n. The roots occur normally in conjugate pairs and only those roots which lead to decay with distance away from the interface in each region are considered. This procedure yields a total of 8 roots, 4 from each region of the interface. Substituting these roots back into the secular equation then yields the relative vectors for the particle displacements, $\alpha_i^{(n)}$, and the potential, $\alpha_4^{(n)}$.

From the above analysis it is clear that 8 partial solutions are required to completely satisfy any and all boundary conditions. Thus the total solution to the layered problem is taken as the sum,

$$\bar{u}_j = \sum_{T,B} C_n \, a_j^{(n)} \, e^{ikb_n X_3} \, e^{ik(X_1 - vt)} \qquad (14)$$

$$\bar{\phi} = \sum_{T,B} C_n \, \alpha_4^{(n)} \, e^{ikb_n X_3} \, e^{ik(X_1 - vt)} \qquad (15)$$

where T,B indicates summation over root numbers, n, for the top and bottom substrates. Each solution is scaled by the appropriate complex constant, C_n, corresponding to the appropriate complex decay constant, b_n.

The complete solution is obtained by satisfying eight boundary conditions. These boundary conditions are as follows:

a. Transverse Mechanical

1. Continuity of transverse displacement at the interface,

$$\bar{U}_2^B = \bar{U}_2^T$$

2. Continuity of transverse stress at the interface,

$$\bar{T}_{32}^B = \bar{T}_{32}^T$$

b. Electrical Continuity

1. Continuity of the normal component of displacement current at the interface,

$$\bar{D}_3^B = \bar{D}_3^T$$

2. Continuity of the scalar potential at the interface,

$$\bar{\phi}^B = \bar{\phi}^T$$

c. Sagittal Plane Mechanical Displacements

1. Continuity of the longitudinal component of mechanical displacement at the interface.

$$\bar{U}_1^B = \bar{U}_1^T$$

2. Continuity of the vertical component of mechanical displacement at the interface,

$$\bar{U}_3^B = \bar{U}_3^T$$

3. Continuity of the shear component of the stress at the interface,

$$\bar{T}_{31}^B = \bar{T}_{31}^T$$

4. Continuity of the compressional component of the stress at the interface,

$$\bar{T}_{33}^B = \bar{T}_{33}^T$$

If the interface is conducting then the conditions on the electric displacement current and potential are changed to reflect a net zero potential at the interface for both the top and bottom regions.

Substituting the summation solutions (14), (15) into the above boundary conditions results in a set of 8 homogeneous equations in the unknown constants, C_n. The matrix coefficients are shown in detail in Table I. The determinant is commonly referred to as the boundary condition determinant. In order to have a non-trivial solution the determinant must equal zero. A computer search routine is used to determine when and if such a velocity exists. After the Stoneley wave velocity has been found (not always possible), the matrix of boundary condition coefficients is used to determine the relative scaling vectors, C_n, and the solution is complete.

3.2 Program Software Development

A completely general set of computer programs were written to obtain Stoneley wave solutions in terms of the top and bottom material piezo-elastic and dielectric material constants. These constants were obtained from well known studies[6] of material properties. Since the material constants are always given with respect to the major axes of the crystal, a subprogram was used to rotate the constants to the appropriate off-axes directions to be studied. After these rotations a search was performed to determine if a Stoneley wave solution existed.

Table I

Stoneley Wave Boundary Condition Determinant

Row	Bottom Substrate Columns m (Four Values)	Top Substrate Columns m (Four Values)
1.	α_2^m	$-\alpha_2^n$
2.	$(c_{32i1} + c_{32i3}b^m)\alpha_i^m + e_{132} + e_{332}b^m)\alpha_4^m$	$-(\hat{c}_{32i1} + \hat{c}_{32i3}b^n)\alpha_i^n - (\hat{e}_{132} + \hat{e}_{332}b^n)\alpha_4^n$
3.	$(C_{3i1} + C_{3i3}b^m)\alpha_i^m - (e_{311} + \hat{e}_{333}b^m)\alpha_4^m$	$-(\hat{c}_{3i1} + \hat{c}_{3i3}b^n)\alpha_i^n + (\hat{e}_{311} + e_{333}b^n)\alpha_4^n$
4.	α_4^m	$-\alpha_4^n$
5.	α_1^m	$-\alpha_1^n$
6.	α_3^m	$-\alpha_3^n$
7.	$(c_{31i1} + c_{31i3}b^m)\alpha_i^m + (e_{131} + e_{331}b^m)\alpha_4^m$	$-\hat{c}_{31i1} + \hat{c}_{31i3}b^n)\alpha_i^n - (\hat{e}_{131} + \hat{e}_{331}b^n)\alpha_4^n$
8.	$(c_{33i1} + c_{33i3}b^m)\alpha_i^m + (e_{133} + e_{333}b^m)\alpha_4^m$	$-\hat{c}_{33i1} + \hat{c}_{33i3}b^n)\alpha_i^n - (\hat{e}_{133} + \hat{e}_{333}b^n)\alpha_4^n$

The Stoneley wave search routine was based upon the value of the determinant of the boundary condition equations. This determinant was evaluated as a function of velocity, a solution being indicated wherever the value of the determinant was zero. For each velocity the secular equation, Eq. (11), was determined and the partial solution vectors and associated decay constants evaluated using a convergent algorithm[7] for solving the eighth order polynominal.

Whenever a Stoneley wave solution was found to exist, an iteration on velocity using a gradient search routine was performed. This technique was able to determine the correct velocity to nine significant digits. After determining the velocity to the desired accuracy, the displacement and potential fields, Eq. (14)-(15), were then plotted as a function of X_3 away from the interface.

4.0 RESULTS

The Stoneley wave formulation and resulting computer programs described in Section 3.0 were used to study propagation in a number of materials considered to be readily available should an appropriate Stoneley wave solution be found. Initially our studies concentrated on verifying the existence of Stoneley waves in simple non-piezoelectric cubic materials and determining search techniques. After these studies more complicated crystal systems such as quartz and $LiNbO_3$ were examined. A considerable amount of computer "data" was accumulated and in the interest of keeping this report readable only a representative amount will be presented.

4.1 Cubic Crystals

As reported by Lim and Musgrave a single crystal material with different orientations for top and bottom materials can support a Stoneley wave. To be described in this section are some prototypic results using the slightly modified set of elastic constants for copper shown in Table II. The specific modification involved only C_{44} which was changed such that the anisotropy ratio

$$\gamma = \frac{2C_{44}}{C_{11} - C_{12}} = 1.52 \quad .$$

Table II
Modified Copper Elastic Constants
($\times 10^{11}$ Nt/m^3)

1.71	1.24	1.24	.	.	.
1.24	1.71	1.24	.	.	.
1.24	1.24	1.71	.	.	.
.	.	.	0.356	.	.
.	.	.	.	0.356	.
.	.	.	.	.	0.356

This modification reflected a ratio which more closely paralleled the ratio found in quartz and $LiNbO_3$ crystals. The general character of the Stoneley wave solutions was not substantially changed by the modification.

Rotated elastic matrices for Stoneley waves were generated using contra-rotated elastic constants for the top and bottom media as shown in Fig. 3. In this case rotation was in the plane of the interface. Shown in Table III are the rotated elastic matrices for ±5° copper.

Table III
Rotated Copper Elastic Constants
($\times 10^{11}$ Nt/m^2)

1.714	1.235	1.239	.	.	±0.0206
1.235	1.714	1.239	.	.	∓0.0206
1.239	1.239	1.71	.	.	.
.	.	.	0.356	.	.
.	.	.	.	0.356	.
±0.0206	∓0.0206	.	.	.	0.3525

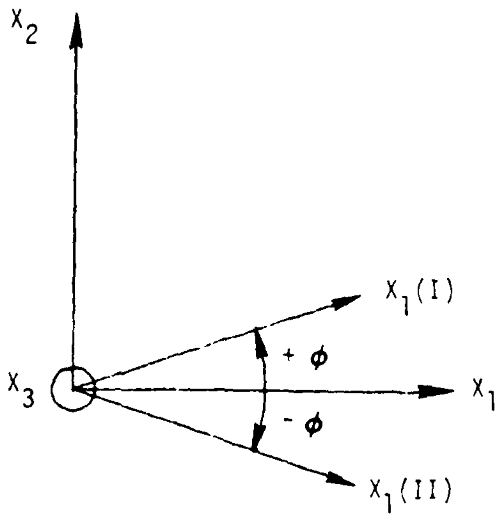


Fig. 3 Rotation of material matrices and vectors for Stoneley wave formulation.

After rotating the material constants, a Stoneley wave search was conducted. For simple cubic materials such as copper, Stoneley waves were always found to exist over a broad range of angular rotations. Solution details for four different angles of rotation are tabulated in Tables IV-VII. In each table the complex secular equation roots (decay constants), partial solution displacement vectors, and complex solution weighting constants are tabulated. The total solution displacements on either side of the interface are plotted in Figs. 4-7.

Examination of Figs. 4-7 as well as Table IV-VII, reveals characteristics which were found to be typical of all Stoneley wave solutions:

1. The Stoneley wave velocity was always numerically greater than the equivalent surface wave velocity but lower than the slowest shear wave velocity.

2. Small angular material rotations always produce solutions with small decay constants, i.e., the wave is not well bound to the interface.

3. Large angular material rotations always produce well bound Stoneley waves with predominantly transverse shear displacements, eventually degenerating into a pure shear displacement wave.

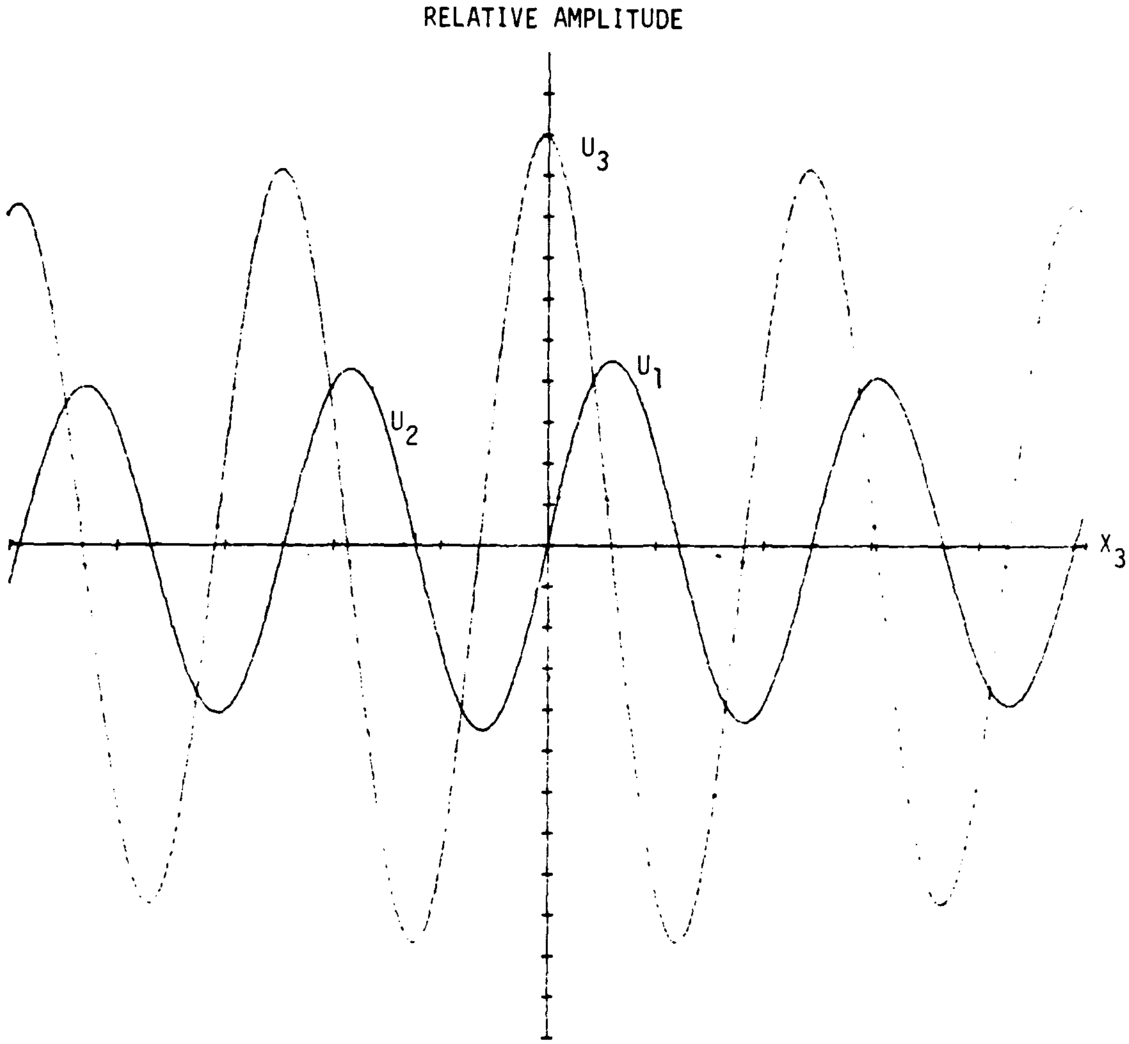


Fig. 4 Stoneley wave displacements for copper $\pm 2^{\circ}$.

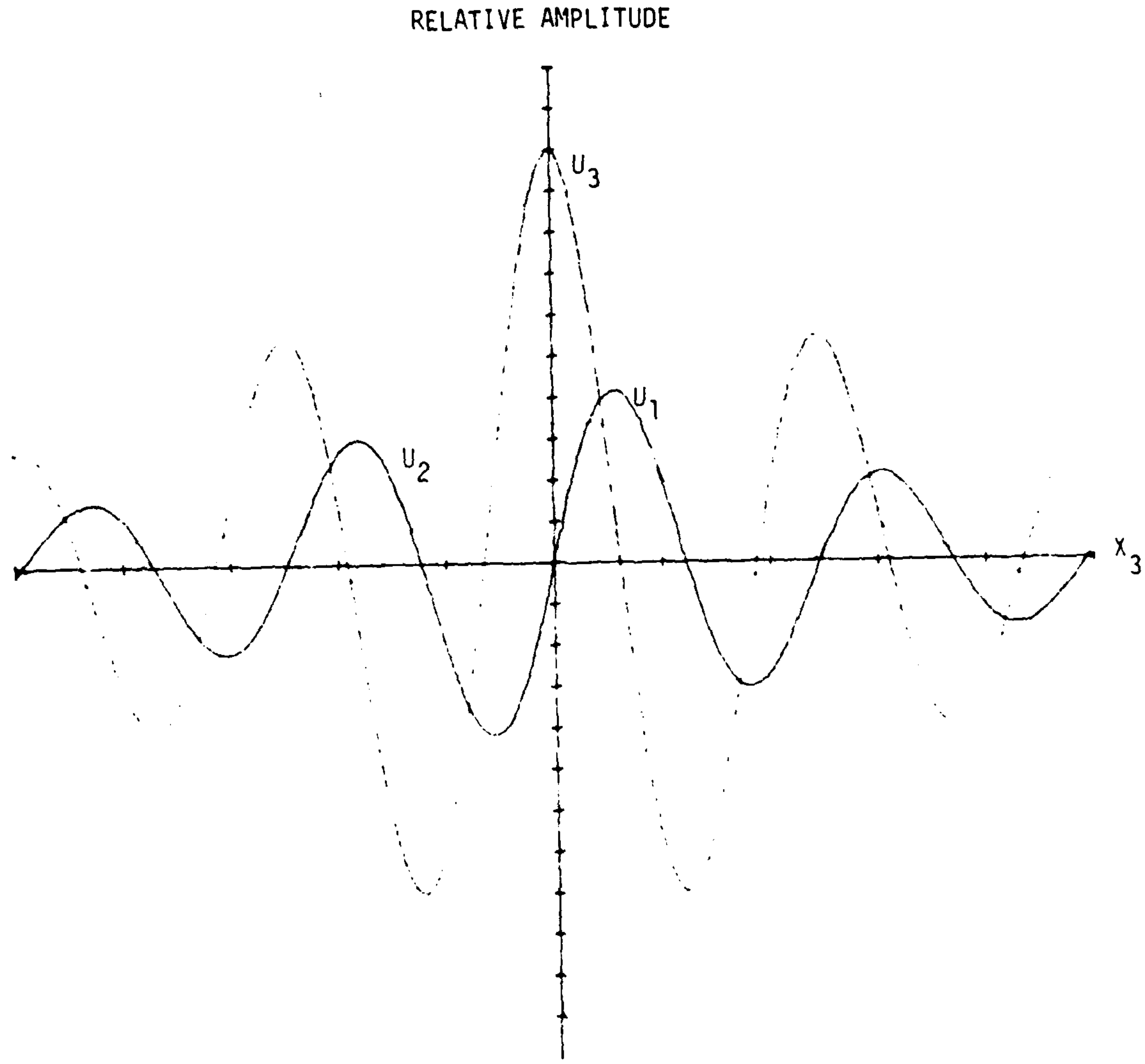


Fig. 5 Stoneley wave displacements for copper $\pm 5^{\circ}$.

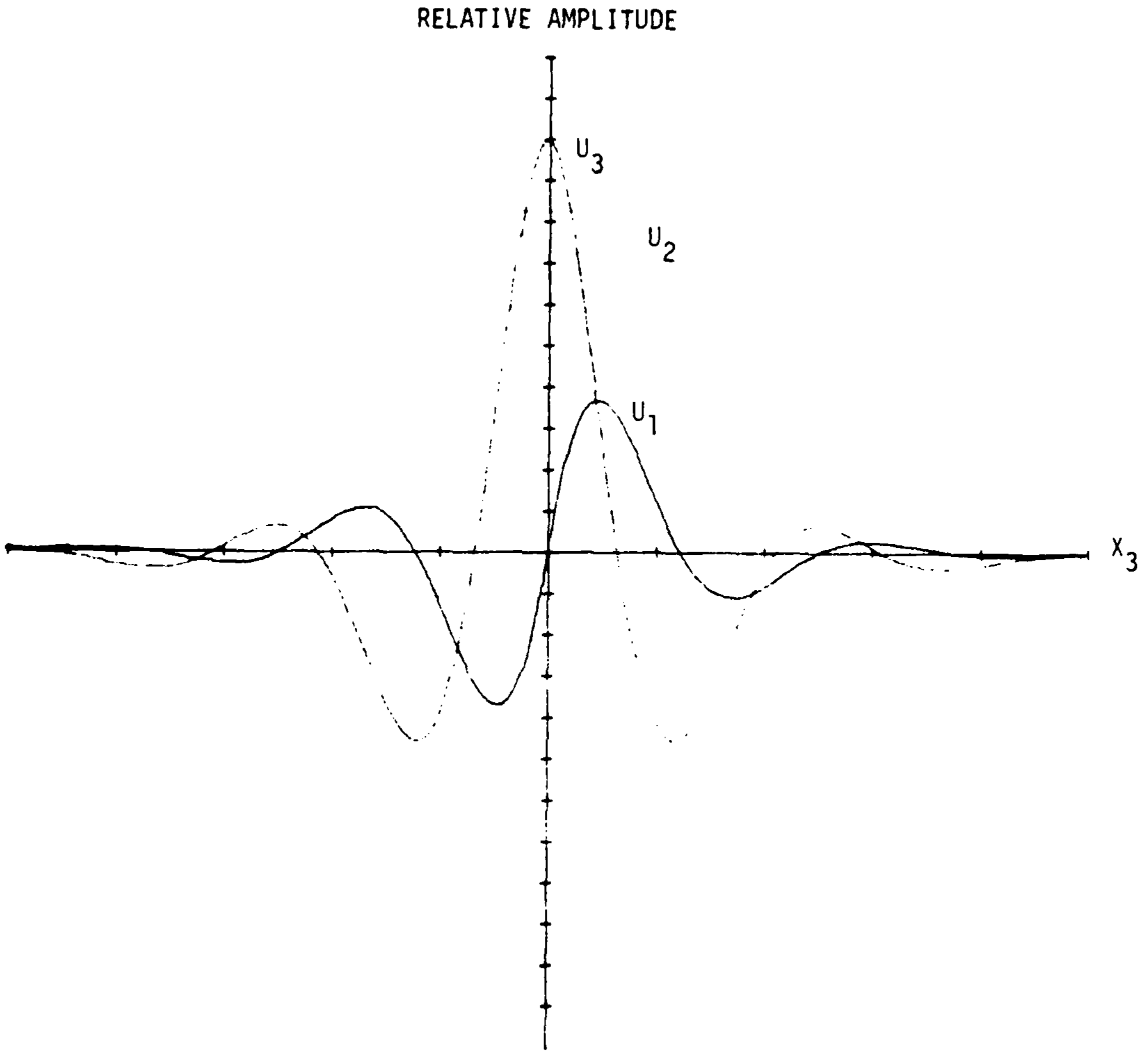


Fig. 6 Stoneley wave displacements for copper ±10°.

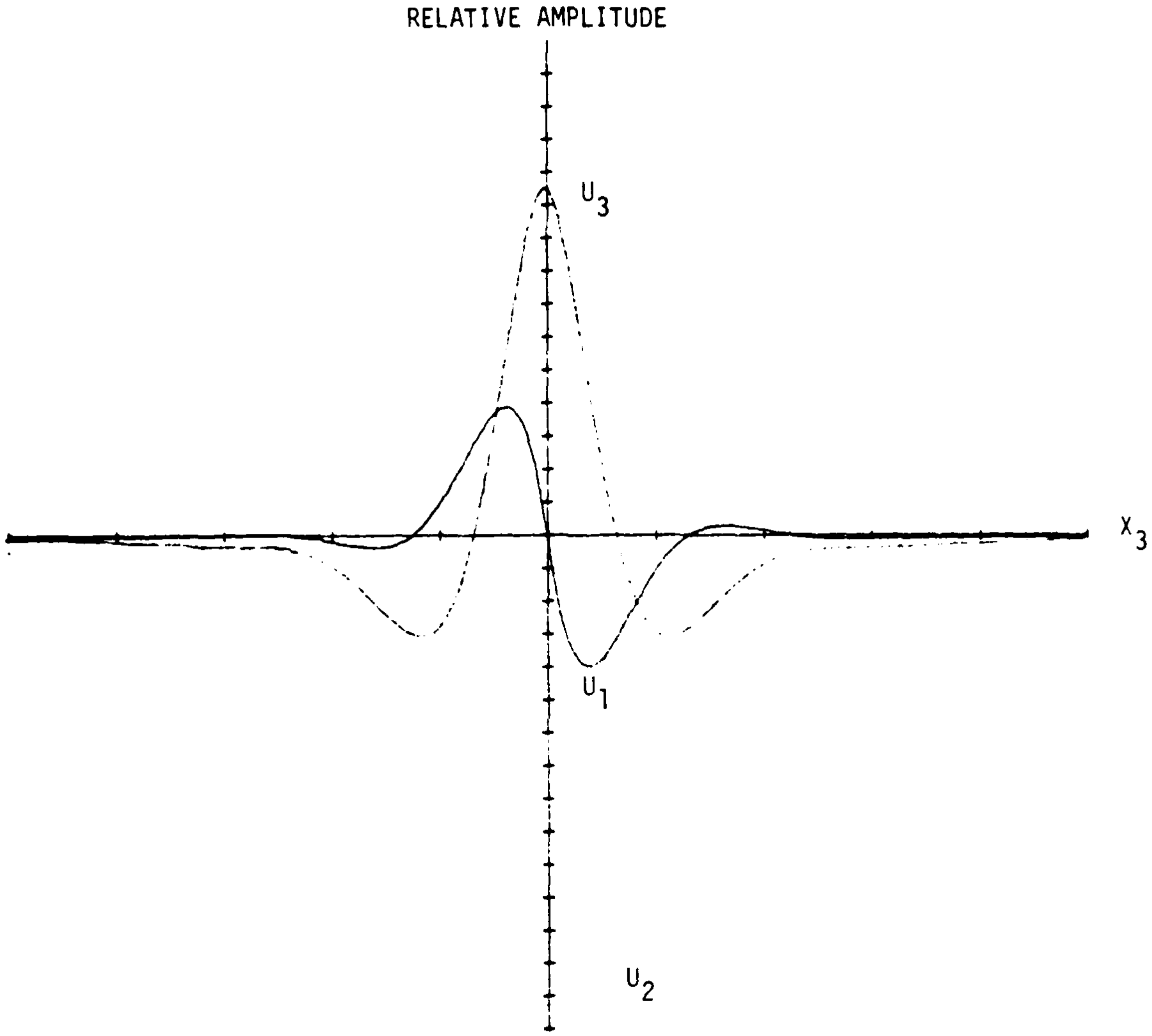


Fig. 7 Stoneley wave displacements for copper $\pm 15^{\circ}$.

Table IV

Stoneley Wave Solution for ±2° Copper

Velocity = 1959.152 m/s

N	Roots b_N	Displacement Vectors α_i	Weighting Factors C_N
1	0.0 - j0.184	α_1 = 1.0 + j0.0 α_2 = 64.736 + j0.0 α_3 = 0.0 - j6.476	0.0 - j0.008
2	0.0 + j0.184	α_1 = 1.0 + j0.0 α_2 = 64.736 + j0.0 α_3 = 0.0 + j6.476	0.0 + j0.008
3	0.408 + j0.007	α_1 = 1.0 + j0.0 α_2 = -0.118 - j0.003 α_3 = 2.192 - j0.032	1.0 + j0.0
4	0.408 + j0.007	α_1 = 1.0 + j0.0 α_2 = 0.118 - j0.003 α_3 = -2.192 + j0.032	-1.0 - j0.008
5	-0.408 - j0.007	α_1 = 1.0 + j0.0 α_2 = -0.118 + j0.003 α_3 = 2.192 - j0.032	1.0 + j0.008
6	-0.408 + j0.007	α_1 = 1.0 + j0.0 α_2 = 0.118 + j0.003 α_3 = 2.192 + j0.032	1.0 + j0.0

Table V

Stoneley Wave Solution for ±5° Copper

Velocity = 1956.870 m/s

N	Roots b_N	Displacement Vectors α_i	Weighting Factors C_N
1	0.0 + j0.170	α_1 = 1.0 + j0.0 α_2 = -32.747 + j0.0 α_3 = 0.0 + j7.514	-0.001 + j0.044
2	0.0 - j0.170	α_1 = 1.0 + j0.0 α_2 = 32.747 + j0.0 α_3 = 0.0 - j7.514	0.001 - j0.044
3	0.404 - j0.043	α_1 = 1.0 + j0.0 α_2 = -0.297 - j0.055 α_3 = -2.186 - j0.212	-1.0 + j0.0
4	0.404	α_1 = 1.0 + j0.0 α_2 = 0.297 - j0.055 α_3 = -2.186 + j0.212	-0.999 - j0.044
5	-0.404 - j0.043	α_1 = 1.0 + j0.0 α_2 = 0.297 + j0.055 α_3 = 2.186 - j0.212	0.999+ j0.044
6	-0.404 + j0.043	α_1 = 1.0 + j0.0 α_2 = 0.297 + j0.055 α_3 = 2.186 + j0.212	1.0 + j0.0

Table VI
Stoneley Wave Solution for ±10° Copper
Velocity = 1936.134 m/s

N	Roots b_N	Displacement Vectors α_i	Weighting Factors C_N
1	0.0 + j0.140	α_1 = 1.0 + j0.0 α_2 = 62.177 + j0.0 α_3 = 0.0 + j16.912	-0.001 + j0.051
2	0.0 - j0.140	α_1 = 1.0 + j0.0 α_2 = 62.177 + j0.0 α_3 = 0.0 - j16.912	0.001 - j0.051
3	0.410 - j0.164	α_1 = 1.0 + j0.0 α_2 = -0.408 - j0.354 α_3 = 1.9333 - j0.697	-1.0 + j0.0
4	0.401 + j0.164	α_1 = 1.0 + j0.0 α_2 = 0.408 - j0.354 α_3 = 1.933 + j0.697	-0.999 - j0.051
5	-0.401 + j0.164	α_1 = 1.0 + j0.0 α_2 = 0.408 + j0.354 α_3 = 1.933 + j0.697	1.0 + j0.0
6	-0.401 - j0.164	α_1 = 1.0 + j0.0 α_2 = -0.408 + j0.354 α_3 = 1.933 - j0.697	0.000 + j0.051

Table VII

Stoneley Wave Solution for ±15° Copper

Velocity = 1892.408 m/s

N	Roots b_N	Displacement Vectors α_i	Weighting Factors C_N
1	0.0 - j0.115	α_1 = 1.0 + j0.0 α_2 = -76.18 + j0.0 α_3 = 0.09 + j14.011	0.002 + j0.055
2	0.0 + j0.115	α_1 = 1.0 + j0.0 α_2 = 76.18 + j0.0 α_3 = 0.0 - j14.011	-0.002 - j0.055
3	+0.407 - j0.285	α_1 = 1.0 + j0.0 α_2 = -0.229 - j0.534 α_3 = 1.566 - j0.927	-1.0 + j0.0
4	+0.407 + j0.285	α_1 = 1.0 + j0.0 α_2 = 0.229 - j0.534 α_3 = -1.566 + j0.927	-0.998 + j0.055
5	-0.407 - j0.285	α_1 = 1.0 + j0.0 α_2 = -0.229 + j0.534 α_3 = 1.566 - j0.927	0.998 - j0.055
6	-0.407 + j0.285	α_1 = 1.0 + j0.0 α_2 = 0.299 + j0.534 α_3 = 1.566 + j0.927	1.0 + j0.0

4. Particle motion in the direction of wave propagation is always zero at the interface.

These characteristics became useful guidelines in future searches conducted on more complex crystal systems. Although numerically modified, all except the last were found to be true in all cases studied.

4.2 Non-Cubic Materials

Following the work on cubic materials described in Section 4.1 a study of non-cubic materials, in particular quartz and $LiNbO_3$ was begun. These materials are of particular interest because they are the more commonly used piezoelectric substrates for surface wave devices.

Our first attempt was to search along major axis directions where simple surface wave solutions were well known. From our studies of simple cubic materials we knew that Stoneley wave solutions were most likely to be found along those directions where the normal surface acoustic wave existed with only two particle motions, both in the saggital plane. In the case of quartz none of the major cuts, X, Y, or Z yielded Stoneley wave solutions.

Failing to find a major cut of quartz which would support a Stoneley wave our attention focused upon $LiNbO_3$. A Stoneley wave search was carried out on the three major cuts of this material and only the Y-cut was found to support Stoneley waves for propagation along the Z axis.

Stoneley wave solutions on YX $LiNbO_3$ were found only over a small range of material angular rotations, i.e., a maximum of ±10 degrees. Shown in Table VIII is a typical solution for ±5°. Because this material is piezoelectric eight complex decay constants are shown along with the eight partial solution vectors. The total displacements and potential for the unshorted interface are plotted in Fig. 8. Shown in Fig. 9 are the displacements and potential when the interface is shorted by a conducting layer of zero physical thickness. In this case the velocity change was comparable to an electromechanical coupling of 1×10^{-4}.

An important characteristic of these waves which was substantially different from earlier results with cubic materials was the low decay constants This is shown in Fig. 9 where clearly more than 25 wavelengths are required for the bound solution to decay.

At the present time our studies on quartz and $LiNbO_3$ are incomplete, however, Stoneley waves have been found in at least one case. The effects of piezoelectricity upon these waves are not well understood and further study is needed. Also other off-axis orientations may yield more suitable cuts with larger decay constants for Stoneley wave devices.

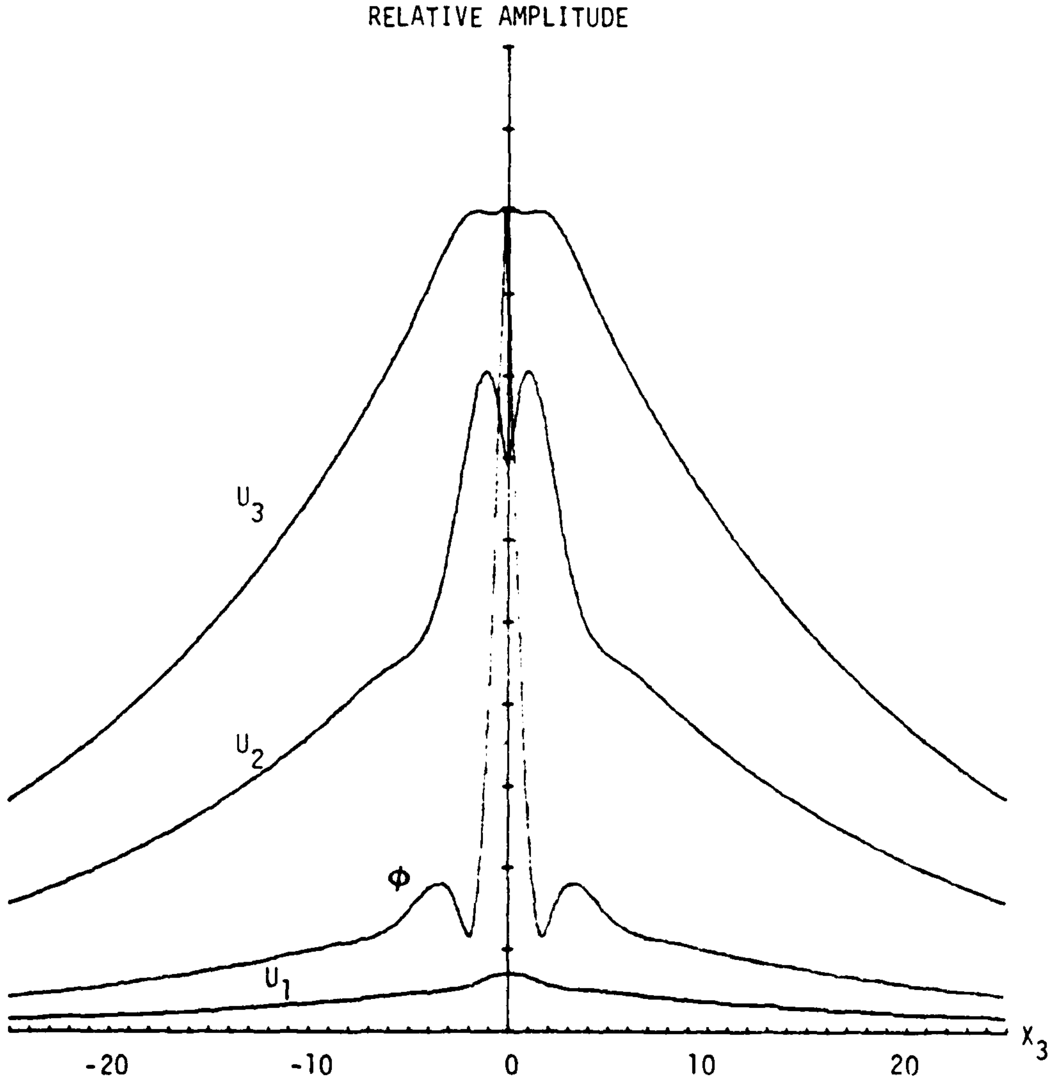


Fig. 8 Unshorted interface Stoneley wave displacements and potential for ±5°, YZ $LiNbO_3$.

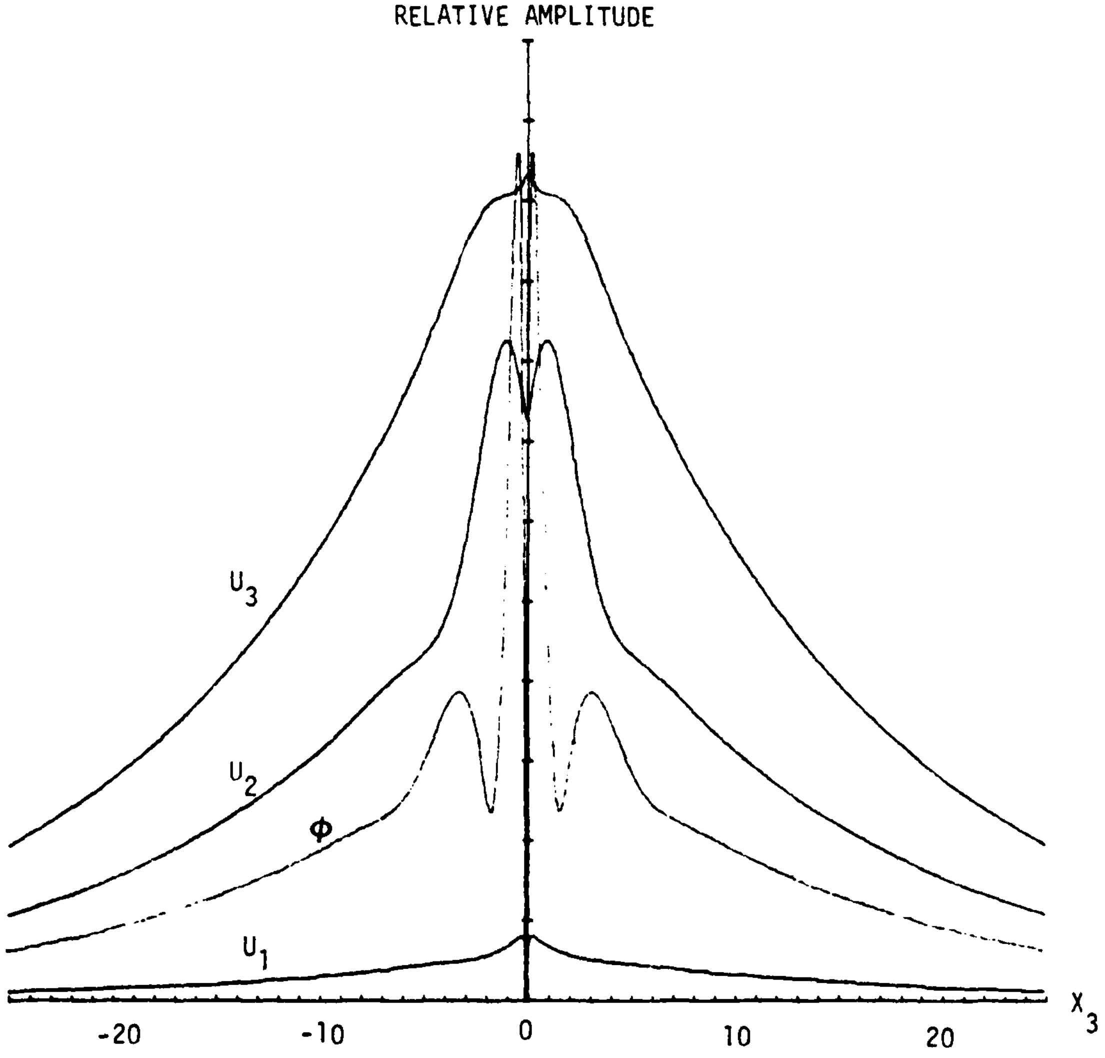


Fig. 9 Shorted interface Stoneley wave displacements and potential for ±5^o, YZ $LiNbO_3$.

Table VIII
Stoneley Wave Solution for ±2° YZ $LiNbO_3$
Velocity = 3527.576 m/s
(Page 1 of 2)

N	Roots b_N	Displacement Vectors α_i	Weighting Factors C_N
1	-0.373 - j1.035	α_1 = 1.121 + j1.165 α_2 = 0.115 - j0.085 α_3 = 1.0 + j0.0 α_4 = 1.041 + j1.934	$-1.009 \times 10^{-2} + j2.004 \times 10^{-6}$
2	-0.373 + j2.035	α_1 = 1.121 - j1.165 α_2 = -0.115 - j0.085 α_3 = 1.0 + j0.0 α_4 = 1.041 - j1.934	$-982 \times 10^{-3} - j2.315 \times 10^{-3}$
3	0.394 - j0.768	α_1 = 0.664 + j0.651 α_2 = 0.160 + j0.043 α_3 = 1.0 + j0.0 α_4 = 0.678 + j1.592	$=2.061 \times 10^{-2} - j3.31 \times 10^{-4}$
4	0.394 + j0.768	α_1 = -0.664 - j0.651 α_2 = 0.160 + j0.043 α_3 = 1.0 + j0.0 α_4 = 0.678 - j1.592	$-1.014 \times 10^{-2} - j4.403 \times 10^{-3}$

Table VIII
Stoneley Wave Solution for ±2° YZ $LiNbO_3$
Velocity = 3527.576 m/s
(Page 2 of 2)

N	Roots b_N	Displacement Vectors α_i	Weighting Factors C_N
5	0.106 - j0.134	α_1 = 0.111 + j0.013 α_2 = 1.396 + j520 α_3 = 1.0 + j0.0 α_4 = 0.103 - j0.726	$-6.027 \times 10^{-2} - j1.264 \times 10^{-1}$
6	0.106 + j0.134	α_1 = 0.111 - j0.013 α_2 = 1.396 + j5.52 α_3 = 1.0 + j0.0 α_4 = 0.103 + j0.726	$-8.764 \times 10^{-2} + j1.092 \times 10^{-1}$
7	-0.057 - j0.009	α_1 = 0.055 + j0.007 α_2 = 0.554 + j0.025 α_3 = 1.0 + j0.0 α_4 = 0.010 - j0.0134	$9.734 \times 10^{-1} + j2.292 \times 10^{-1}$
8	-0.057 + j0.009	α_1 = 0.055 - j0.007 α_2 = 0.554 + j0.025 α_3 = 1.0 + j0.0 α_4 = 0.010 + j0.0134	1.0 + j0.0

5.0 CONCLUSIONS AND RECOMMENDATIONS

The objective of this study was to assess the feasibility of developing a single crystal pressure sensor utilizing Stoneley waves. A theoretical study of Stoneley wave propagation was carried out on cubic material as well as non-cubic but piezoelectric quartz and $LiNbO_3$. The results of these studies showed that strongly bound Stoneley waves could propagate along major axes of cubic materials. Extending the analysis to the non-cubic materials, quartz and $LiNbO_3$, revealed that the major axes of quartz could not support Stoneley waves while only the YZ cut of $LiNbO_3$ could support Stoneley wave propagation. The analysis for $LiNbO_3$ showed that the waves would have an electromechanical coupling coefficient of 1×10^{-4} and would require approximately 50 wavelengths of material to isolate the interface from the outer surfaces of the crystal structure.

In view of the level of effort we find these results encouraging but incomplete in the sense that we were not able to study many other potential materials and orientations. We recommend the following tasks for future work in this area:

1. To develop a better understanding of the role played by crystal anisotropy, surface wave behavior, and bulk wave properties in Stoneley wave propagation.

2. To utilize this knowledge to develop better and less time consuming Stoneley wave search methods.

3. To examine other materials such as silicon and GaAs for possible Stoneley wave propagation.

6.0 REFERENCES

1. E.J. Staples, J. Wise, J.S. Schoenwald, and T.C. Lim, "Surface Acoustic Wave Underwater Sound Sensors," Proceedings of the 1979 Ultrasonic Symposium, p. 870-873, CH1482-9/79/0000.

2. W.W. Johnson, "The Propagation of Stoneley and Rayleigh Waves in Anisotropic Elastic Media," Bull. Seis. Soc. Amer. 60, pp. 1105-1122 (1970).

3. T.E. Owen, "The Existence of Stoneley Waves," Prop. Appl. Mat. Res. (GB), 6, p. 69 (1964).

4. T.C. Lim and M.J.P. Musgave, "Stoneley Waves in Anisotropic Media," Nature, 225, p. 372 (1970).

5. "IRE Standards on Piezoelectric Crystals- the Piezoelectric Vibrator: Definitions and Methods of Measurement," Proc. IRE, 45, pp. 353-358 (1957).

6. Microwave Acoustics Handbook, 1A, Surface Wave Velocities, Air Force Cambridge Research Laboratories, L.G. Hanscom Field, Bedore, Mass (1973).

7. J.B. Moore, "A Convergent Algorithm for Solving Polynominal Equations," J. Assoc. Computing Machinery, 14, No. 2, pp. 311-315 (1967).